η transitions between charmonia with meson loop contributions

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We study the η transitions between $\psi(4040/4160)$ and J/ψ by introducing charmed meson loops in an effective Lagrangian approach to enhance the decay amplitudes. The branching fractions $\mathcal{B}[\psi(4040) \to J/\psi\eta]$ and $\mathcal{B}[\psi(4160) \to J/\psi\eta]$ estimated in this paper can remarkably explain the experimental measurements of Belle and BESIII within a reasonable parameter range. The η' transition between $\psi(4160)$ and J/ψ is also investigated, and the branching fraction is under the upper limit of CLEO, which can be tested by future experiments.

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I. INTRODUCTION

Among many heavy quarknonia, the chamonium sector especially has much abundant spectroscopy and decay modes observed [1]. In their mass range, there are also many discrepancies between theoretical predictions and experimental measurements because of the non-pertubative property of Quantum Chromodynamics (QCD). The study of spectroscopy and decay behavior of the charmonia undoubtedly enrich our knowledge of how QCD works in hadron physics.

When considering the decay process $\psi_1 \to \psi_2\mathcal{P}$, the direct coupling among the initial and final charmonia, ψ_1 and ψ_2, and a light chiral meson, $\mathcal{P}$, is highly suppressed due to the OZI rule. Because Belle and BESIII have recently observed branching fractions for some processes of this kind, of the order of 10^{-3}, hence we need to consider other mechanism which enhances this type of decay amplitude. The charmonia, whose masses are above the threshold of a charmed meson pair, dominantly decay into a pair of charmed mesons, which can couple with a light meson and a charmonium by exchanging a proper charmed meson in the final states. The contribution from such a structure, i.e., meson loop contribution, is dominant in this decay and becomes important in understanding decay behaviors of higher charmonia.

Taking $\psi(3770)$ as an example, which is the first charmonium above the threshold of open charmed mesons, the BES Collaboration announced that the branching fraction of its non-$D\bar{D}$ decay is $\mathcal{B}[\psi(3770) \to \text{non}-D\bar{D}] = (14.7\pm3.2)\%$ [2–5]. Such a large non-$D\bar{D}$ branching fraction is several times larger than expected in theory [6]. To resolve this discrepancy, the authors in Refs. [7, 8] have taken account of the charmed meson loop, where the initial charmonium $\psi(3770)$ decays into a charmed meson pair $D\bar{D}$ and this pair couples to a vector and/or pseudoscalar meson by exchanging a D meson. After including the meson loop contributions, the large non-$D\bar{D}$ branching fraction of $\psi(3770)$ can be nicely explained. The decay mode $\psi(3770) \to J/\psi\mathcal{P}$ and the lineshape around $\psi(3770)$ have been studied with meson loop contributions in Ref. [9].

Even though the measurements of the higher charmonia are not yet enough to discuss η transitions, there appear some experiments of this kind. In the International Conference on High Energy Physics, the Belle Collaboration reported their measurements for η transitions between $\psi(4160/4040)$ and J/ψ [10]. They announced that $\mathcal{B}[\psi(4040) \to \eta J/\psi] \cdot \Gamma_{e^+e^-}(\psi(4040)) = 5.1 \pm 0.8 \pm 1.1$ eV or $12.4 \pm 1.2 \pm 1.2$ eV with different fitting parameters to the data. The corresponding results for $\psi(4160)$ are $\mathcal{B}[\psi(4160) \to \eta J/\psi] \cdot \Gamma_{e^+e^-}(\psi(4160)) = 4.1\pm0.5\pm0.8$ eV or $15.2\pm1.2\pm1.5$ eV. Taking $\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV and $\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV, one obtains the branching ratios as $\mathcal{B}[\psi(4040) \to J/\psi\eta] = (0.59 \pm 0.11 \pm 0.14)\%$ or $(1.44 \pm 0.18 \pm 0.18)\%$ and $\mathcal{B}[\psi(4160) \to J/\psi\eta] = (0.50 \pm 0.07 \pm 0.11)\%$ or $(1.83 \pm 0.21 \pm 0.24)\%$. Before this measurement, only the upper limits of branching ratios for $\psi(4040) \to \eta J/\psi$ and $\psi(4160) \to \eta J/\psi$ were reported by the CLEO Collaboration, which are $< 7 \times 10^{-3}$ and $< 8 \times 10^{-3}$ [11], respectively. Recently, the BESIII Collaboration also analyzed the production of $e^+e^- \to \eta J/\psi$ at a center-of-mass energy of $\sqrt{s} = 4.009$ GeV. Because the Born cross section is reported to be $(32.1 \pm 2.8 \pm 1.3)$ pb [12], the corresponding fractional transition rate is $\mathcal{B}[\psi(4040) \to \eta J/\psi] = (5.2 \pm 0.5 \pm 0.2 \pm 0.5) \times 10^{-3}$, which is consistent with the first solution of the Belle Collaboration and measurement by CLEO.

Similar to the case of $\psi(3770)$, $\psi(4040)$ and $\psi(4160)$ are above the threshold of charmed meson pairs, and dominantly decay into these. The experimental measurements stimulate us to study the η transition between $\psi(4040/4160)$ and J/ψ with the meson loop mechanism, which is essential to understand the hidden charm decay behavior like higher charmonia.

This paper is organized as follows. After introduction, a brief review of meson loop mechanism is presented and the corresponding amplitudes are calculated using an effective Lagrangian in Section II. Our numerical results of the branching ratios are given in Section III. Section IV is devoted to summary.

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II. η TRANSITION OF $\psi(4040)$ AND $\psi(4160)$

The meson loop effect plays a crucial role in understanding the η transition between the higher charmonium and J/ψ. Taking $\psi(4040) \to J/\psi\eta$ as an example, involvement of the meson loop in the decay is depicted in Fig. 1. The charmonium $\psi(4040)$ is decomposed into $D^{(*)}\bar{D}^{(*)}$ and by exchanging D or D^* meson, the charmed meson pair converts itself into $J/\psi\eta$.

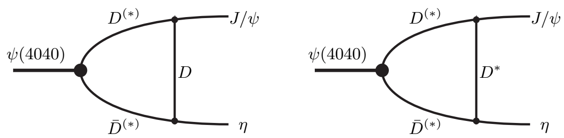

FIG. 1: The typical meson loop diagrams contributing to $\psi(4040) \to J/\psi\eta$. The initial $\psi(4040)$ couples with a charmed meson pair $D^{(*)}\bar{D}^{(*)}$, and by exchanging the D meson (left) or D^* meson (right), the charmed meson pair converts itself into $J/\psi\eta$ in the final state.

The effective Lagrangian approach is adopted to evaluate the meson loop contributions to higher charmonia decay into $J/\psi\eta$ as shown in Fig. 1. Utilizing the heavy quark limit and chiral symmetry, the involved effective Lagrangians read as [13, 14]:

$$
\begin{aligned}
\mathcal{L}_{\psi\mathcal{D}^{(*)}\mathcal{D}^{(*)}} &= ig_{\psi\mathcal{D}\mathcal{D}}\psi_\mu\left(\partial^\mu\mathcal{D}\mathcal{D}^\dagger - \mathcal{D}\partial^\mu\mathcal{D}^\dagger\right) - g_{\psi\mathcal{D}^*\mathcal{D}}\varepsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu \\
&\quad\times\left(\partial_\alpha\mathcal{D}^*_\beta\mathcal{D}^\dagger + \mathcal{D}\partial_\alpha\mathcal{D}^{*\dagger}_\beta\right) - ig_{\psi\mathcal{D}^*\mathcal{D}^*}\Big\{\psi^\mu\Big(\partial_\mu\mathcal{D}^{*\nu}\mathcal{D}^{*\dagger}_\nu \\
&\quad-\mathcal{D}^{*\nu}\partial_\mu\mathcal{D}^{*\dagger}_\nu\Big) + \left(\partial_\mu\psi_\nu\mathcal{D}^{*\nu} - \psi_\nu\partial_\mu\mathcal{D}^{*\nu}\right)\mathcal{D}^{*\mu\dagger} \\
&\quad+\mathcal{D}^{*\mu}\Big(\psi^\nu\partial_\mu\mathcal{D}^{*\dagger}_\nu - \partial_\mu\psi_\nu\mathcal{D}^{*\nu\dagger}\Big)\Big\}, \\
\mathcal{L}_{\mathcal{D}^{(*)}\mathcal{D}^{(*)}\mathcal{P}} &= -ig_{D^*DP}(\bar{\mathcal{D}}\partial_\mu\mathcal{P}\mathcal{D}^{*\mu} - \bar{\mathcal{D}}^{*\mu}\partial_\mu\mathcal{P}\mathcal{D}) \\
&\quad+\frac{1}{2}g_{D^*D^*P}\epsilon_{\mu\nu\alpha\beta}\bar{\mathcal{D}}^{*\mu}\partial^\nu\mathcal{P}\overleftrightarrow{\partial}^\alpha\mathcal{D}^{*\beta},
\end{aligned}
\tag{1}
$$

with $\mathcal{D}^{(*)} = \left(D^{(*)0}, D^{(*)+}, D_s^{(*)+}\right)$. Considering η and η' mixing, one has $\mathcal{P}$ in the form,

$$
\mathcal{P} = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \alpha\eta + \beta\eta' & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \alpha\eta + \beta\eta' & K^0 \\ K^- & \bar{K}^0 & \gamma\eta + \delta\eta' \end{pmatrix}, \tag{2}
$$

where

$$
\begin{aligned}
\alpha &= \frac{\cos\theta - \sqrt{2}\sin\theta}{\sqrt{6}}, \ \beta = \frac{\sin\theta + \sqrt{2}\cos\theta}{\sqrt{6}}, \\
\gamma &= \frac{-2\cos\theta - \sqrt{2}\sin\theta}{\sqrt{6}}, \ \delta = \frac{-2\sin\theta + \sqrt{2}\cos\theta}{\sqrt{6}}
\end{aligned}
\tag{3}
$$

and we adopt $\theta = -19.1^\circ$ in the present work [15, 16].

In the symmetric limit, the coupling constants between J/ψ and charmed mesons satisfy $g_{\psi DD} = g_{\psi D^*D^*}m_D/m_{D^*} = g_{\psi D^*D}\sqrt{m_D m_{D^*}} = m_{J/\psi}/f_{J/\psi}$ with $m_{J/\psi}$ and $f_{J/\psi}$ being the mass and decay constant of J/ψ. On the other hand, the coupling between pseudoscalar meson and charmed mesons can be related to the gauge coupling constant g by $g_{\mathcal{P}\mathcal{D}^*\mathcal{D}^*} = g_{\mathcal{P}\mathcal{D}^*\mathcal{D}}/\sqrt{m_D m_{D^*}} = 2g/f_\pi$ with $g = 0.59$ and $f_\pi = 132$ MeV. The coupling constants between higher charmonia, such as $\psi(4040)$ and $\psi(4160)$, and charmed mesons are evaluated by the partial decay width assuming that these two charmonia dominantly decay into $D\bar{D}$, $D^*\bar{D} + h.c.$, and $D^*\bar{D}^*$ due to the restriction of the phase space. Furthermore the BaBar Collaboration has measured the ratios between these decay modes for $\psi(4040)$ and $\psi(4160)$ [17], which are $\mathrm{Br}(\psi(4040) \to D\bar{D})/\mathrm{Br}(\psi(4040) \to D^*\bar{D}) = 0.24 \pm 0.05 \pm 0.12$, $\mathrm{Br}(\psi(4040) \to D^*\bar{D}^*)/\mathrm{Br}(\psi(4040) \to D^*\bar{D}) = 0.18 \pm 0.14 \pm 0.03$ and $\mathrm{Br}(\psi(4160) \to D\bar{D})/\mathrm{Br}(\psi(4160) \to D^*\bar{D}^*) = 0.02$, $\mathrm{Br}(\psi(4160) \to D^*\bar{D})/\mathrm{Br}(\psi(4160) \to D^*\bar{D}^*) = 0.34$. Given the total decay width $\Gamma_{\psi(4040)} = 80$ MeV and $\Gamma_{\psi(4160)} = 103$ MeV, one obtains $|g_{\psi(4040)DD}| = 2.13$, $|g_{\psi(4040)D^*D}| = 1.70\ \mathrm{GeV}^{-1}$, $|g_{\psi(4040)D^*D^*}| = 3.34$, $|g_{\psi(4160)DD}| = 0.57$, $|g_{\psi(4160)D^*D}| = 0.77\ \mathrm{GeV}^{-1}$, and $|g_{\psi(4160)D^*D^*}| = 2.23$.

With the Lagrangians listed above, we can obtain the hadronic decay amplitudes for $\psi(4040)(p_0) \rightarrowtail [D^{(*)}(p_1)\bar{D}^{(*)}(p_2)]D^{(*)}(q) \rightarrowtail J/\psi(p_3)\eta(p_4)$,

$$
\begin{aligned}
\mathcal{A}^{D^*}_{D\bar{D}} &= (i)^3\int\frac{d^4q}{(2\pi)^4}[ig_{\psi' DD}\epsilon^\mu_{\psi'}(ip_{1\mu} - ip_{2\mu})][-g_{J/\psi D^*D} \\
&\times\ \varepsilon_{\rho\nu\alpha\beta}(ip_3^\rho)\epsilon^\nu_{J/\psi}(iq^\alpha)][-ig_{D^*D\eta}(ip_{4\lambda})] \\
&\times\ \frac{1}{p_1^2 - m_D^2}\frac{1}{p_2^2 - m_D^2}\frac{-g^{\beta\lambda} + q^\beta q^\lambda/m^2_{D^*}}{q^2 - m^2_{D^*}}\mathcal{F}^2(q^2, m^2_{D^*}), \\
\mathcal{A}^{D}_{D\bar{D}^*} &= (i)^3\int\frac{d^4q}{(2\pi)^4}[-g_{\psi' D^*D}\varepsilon_{\rho\mu\alpha\beta}(-ip_0^\rho)\epsilon^\mu_{\psi'}(ip_2^\alpha)] \\
&\times\ [ig_{J/\psi DD}\epsilon^\nu_{J/\psi}(iq_\nu + ip_{1\nu})][-ig_{D^*D\eta}(-ip_{4\lambda})] \\
&\times\ \frac{1}{p_1^2 - m_D^2}\frac{-g^{\beta\lambda} + p_2^\beta p_2^\lambda/m^2_{D^*}}{p_2^2 - m^2_{D^*}}\frac{1}{q^2 - m_D^2}\mathcal{F}^2(q^2, m_D^2), \\
\mathcal{A}^{D^*}_{D\bar{D}^*} &= (i)^3\int\frac{d^4q}{(2\pi)^4}[-g_{\psi' D^*D}\varepsilon_{\rho\mu\alpha\beta}(-ip_0^\rho)\epsilon^\mu_{\psi'}(ip_2^\alpha)] \\
&\times\ [-g_{J/\psi D^*D}\varepsilon_{\lambda\nu\theta\phi}(ip_3^\lambda)\epsilon^\nu_{J/\psi}(iq^\theta)][\frac{1}{2}g_{D^*D^*\eta}\varepsilon_{\delta\tau\eta\omega} \\
&\times\ (ip_4^\tau)(-iq^\eta + ip_2^\eta)]\frac{1}{p_1^2 - m_D^2}\frac{-g^{\beta\delta} + p_2^\beta p_2^\delta/m^2_{D^*}}{p_2^2 - m^2_{D^*}} \\
&\times\ \frac{-g^{\phi\omega} + q^\phi q^\omega/m^2_{D^*}}{q^2 - m^2_{D^*}}\mathcal{F}^2(q^2, m^2_{D^*}), \\
\mathcal{A}^{D^*}_{D^*\bar{D}} &= (i)^3\int\frac{d^4q}{(2\pi)^4}[-g_{\psi' D^*D}\varepsilon_{\tau\mu\alpha\beta}(-ip_0^\tau)\epsilon^\mu_{\psi'}(ip_1^\alpha)] \\
&\times\ [-ig_{J/\psi D^*D^*}\epsilon^\gamma_{J/\psi}(g_{\rho\lambda}(-ip_{1\nu} - iq_\nu)) + g_{\rho\nu}(ip_{3\lambda} + ip_{1\lambda}) \\
&+\ g_{\nu\lambda}(iq_\rho - ip_{3\rho})][-ig_{D^*D\eta}(ip_{4\delta})]\frac{-g^{\beta\rho} + p_1^\beta p_1^\rho/m^2_{D^*}}{p_1^2 - m^2_{D^*}} \\
&\times\ \frac{1}{p_2 - m_D^2}\frac{-g^{\delta\lambda} + q^\delta q^\lambda/m^2_{D^*}}{q^2 - m^2_{D^*}}\mathcal{F}^2(q^2, m^2_{D^*}), \\
\mathcal{A}^{D}_{D^*\bar{D}^*} &= (i)^3\int\frac{d^4q}{(2\pi)^4}[-ig_{\psi' D^*D^*}\epsilon^\mu_{\psi'}(g_{\rho\lambda}(ip_{1\mu} - ip_{2\mu}) \\
&+\ g_{\mu\rho}(-ip_{0\lambda} - ip_{1\lambda}) + g_{\mu\lambda}(ip_{2\rho} + ip_{0\rho}))]
\end{aligned}
$$

$$
\begin{aligned}
&\times\ [-g_{J/\psi D^* D}\varepsilon_{\delta\nu\alpha\beta}(ip_3^\delta)\epsilon^\nu_{J/\psi}(-ip_1^\alpha)][-ig_{D^* D\eta}(-ip_{4\tau})]\\
&\times\ \frac{-g^{\beta\rho}+p_1^\beta p_1^\rho/m^2_{D^*}}{p_1^2-m^2_{D^*}}\frac{-g^{\tau\lambda}+p_2^\tau p_2^\lambda/m^2_{D^*}}{p_2^2-m^2_{D^*}}\\
&\times\ \frac{1}{q^2-m_D^2}\mathcal{F}^2(q^2,m_D^2)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{A}^{D^*}_{D^*\bar{D}^*} &= (i)^3\int\frac{d^4q}{(2\pi)^4}[-ig_{\psi' D^* D^*}\epsilon^\mu_{\psi'}(g_{\rho\lambda}(ip_{1\mu}-ip_{2\mu})\\
&+\ g_{\mu\rho}(-ip_{0\lambda}-ip_{1\lambda})+g_{\mu\lambda}(ip_{2\rho}+ip_{0\rho}))]\\
&\times\ [-ig_{J/\psi D^* D^*}\epsilon^\nu_{J/\psi}(g_{\alpha\beta}(-ip_1^\nu-iq^\nu))+g_{\beta\nu}(ip_{3\alpha}+ip_{1\alpha})\\
&+\ g_{\alpha\nu}(iq_\beta-ip_{3\beta})][\frac{1}{2}g_{D^* D^*\eta}\varepsilon_{\delta\tau\eta\omega}(ip_4^\tau)(-iq^\eta+ip_2^\eta)]\\
&\times\ \frac{-g^{\rho\beta}+p_1^\beta p_1^\rho/m^2_{D^*}}{p_1^2-m^2_{D^*}}\frac{-g^{\lambda\delta}+p_2^\lambda p_2^\delta/m^2_{D^*}}{p_2^2-m^2_{D^*}}\\
&\times\ \frac{-g^{\alpha\omega}+q^\alpha q^\omega/m^2_{D^*}}{q^2-m^2_{D^*}}\mathcal{F}^2(q^2,m^2_{D^*}), \qquad (4)
\end{aligned}
$$

where the amplitude $\mathcal{A}^{M_3}_{M_1M_2}$ corresponds to the process in which the initial $\psi(4040)$ is decomposed into a charmed meson pair M_1M_2 by exchanging M_3, and then this meson pair converts itself into $J/\psi\eta$ in the final state. The form factor $\mathcal{F}(q^2,m_E^2)=(m_E^2-\Lambda^2)/(q^2-\Lambda^2)$ is introduced to evade infrared divergence in the loop integrals as well as to describe the structure effects and off shell influence of the exchanged mesons. The parameter Λ can be reparameterized as $\Lambda=m_E+\alpha\Lambda_{QCD}$ with $\Lambda_{QCD}=220$MeV, and the unique parameter α is taken to be of the order of unity [18].

To estimate the branching ratios of $\psi'\to J/\psi\eta$ ($\psi'=\{\psi(4040),\psi(4160)\}$) derived from hadronic loops, we summarize the amplitudes as,

$$
\begin{aligned}
\mathcal{M}_1 &= \mathcal{A}^{D^*}_{D\bar{D}}=g^{DD}_{\psi' J/\psi\eta}\varepsilon_{\mu\nu\alpha\beta}\epsilon^\mu_{\psi'}\epsilon^\nu_{J/\psi}p^\alpha_{J/\psi}p^\beta_\eta,\\
\mathcal{M}_2 &= \mathcal{A}^{D}_{D\bar{D}^*}+\mathcal{A}^{D^*}_{D\bar{D}^*}+\mathcal{A}^{D^*}_{D^*\bar{D}}=g^{D^*D}_{\psi' J/\psi\eta}\varepsilon_{\mu\nu\alpha\beta}\epsilon^\mu_{\psi'}\epsilon^\nu_{J/\psi}p^\alpha_{J/\psi}p^\beta_\eta,\\
\mathcal{M}_3 &= \mathcal{A}^{D}_{D^*\bar{D}^*}+\mathcal{A}^{D^*}_{D^*\bar{D}^*}=g^{D^*D^*}_{\psi' J/\psi\eta}\varepsilon_{\mu\nu\alpha\beta}\epsilon^\mu_{\psi'}\epsilon^\nu_{J/\psi}p^\alpha_{J/\psi}p^\beta_\eta, \qquad (5)
\end{aligned}
$$

where $\mathcal{M}_1$, $\mathcal{M}_2$ and $\mathcal{M}_3$ are the amplitudes corresponding to the channels $D\bar{D}$, $D^*\bar{D}+h.c.$ and $D^*\bar{D}^*$, respectively. The amplitudes can be reduced to a simple Lorentz structure $\varepsilon_{\mu\nu\alpha\beta}\epsilon^\mu_{\psi'}\epsilon^\nu_{J/\psi}p^\alpha_{J/\psi}p^\beta_\eta$ multiplied with the coupling constants $g^{D^{(*)}D^{(*)}}_{\psi' J/\psi\eta}$, which can be evaluated by the loop integrals.

Since we can obtain only the absolute values of the coupling between $\psi(4040/4160)$ and charmed mesons, we should, in general, introduce phase angles among different amplitudes. The total amplitudes can be expressed as

$$\mathcal{M}_{\rm tot}=\mathcal{M}_1+e^{i\phi_1}\mathcal{M}_2+e^{i\phi_2}\mathcal{M}_3, \qquad (6)$$

and the partial decay width is

$$\Gamma=\frac{1}{3}\frac{1}{8\pi}\frac{|\vec{p}_\eta|}{m^2_{\psi'}}|\overline{\mathcal{M}_{\rm tot}}|^2, \qquad (7)$$

where the overline indicates the sum over the polarization vectors of ψ' and J/ψ and $|\vec{p}_\eta|=\lambda^{1/2}(m^2_{\psi'},m^2_{J/\psi},m^2_\eta)/(2m_{\psi'})$ with $\lambda(x,y,z)=x^2+y^2+z^2-2xy-2xz-zyz$.

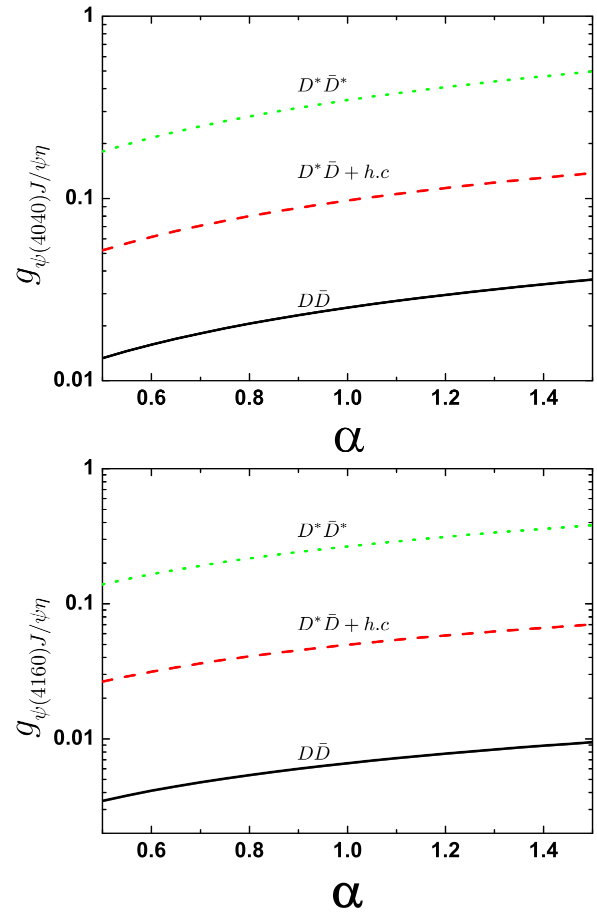

FIG. 2: (color online) The α dependence of the absolute values of coupling constants $g_{\psi' J/\psi\eta}$ derived from meson loop contributions to $\psi(4040)\to J/\psi\eta$ (upper panel) and $\psi(4160)\to J/\psi\eta$ (lower panel). Different intermediate channels are considered; the green dotted, red dashed and black solid curves are corresponding to contributions from $D^*\bar{D}^*$, $D^*\bar{D}+h.c.$ and $D\bar{D}$ intermediates, respectively.

III. NUMERICAL RESULTS AND DISCUSSION

The coupling constant $g^{D^{(*)}D^{(*)}}_{\psi' J/\psi\eta}$ defined in Eq. (5) can be evaluated by estimating the corresponding loop integrals. In general, the evaluated coupling constants from meson loop contributions are complex. In Fig. 2, we show the absolute values of the coupling constants corresponding to different intermediate channels. For $\psi(4040)\to J/\psi\eta$ process, the coupling constant corresponding to $D^*\bar{D}+h.c$ channel is about 3 times larger than that for $D\bar{D}$ channel, while the one for $D^*\bar{D}^*$ is one order larger than that for $D\bar{D}$ channel. The coupling constants for $\psi(4160)J/\psi\eta$ are very similar to those for the $\psi(4040)\to J/\psi\eta$. The dominant contribution comes from the process with $D^*\bar{D}^*$ channel and the one corresponding to $D\bar{D}$ is very small and can be neglected.

With the coupling evaluated above, one can estimate the branching ratios of $\psi(4040/4160)\to J/\psi\eta$. The phase angles in Eq. (6) are kept unknown, and the sign of the coupling constant for $\psi' D^{(*)}D^{(*)}$, $\psi'=\{\psi(4040),\psi(4160)\}$ can also be absorbed by these phase angles. Since the contributions from

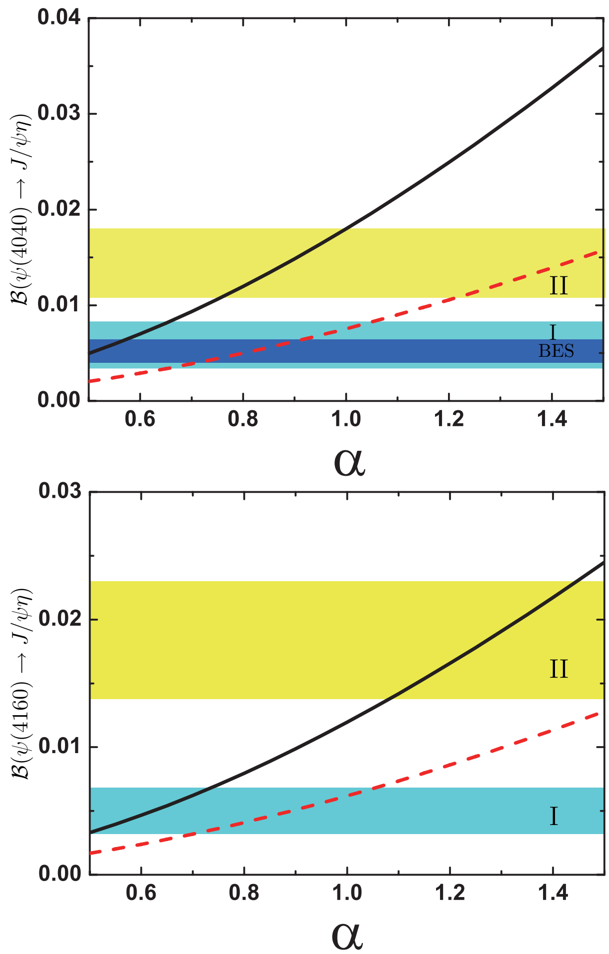

FIG. 3: (color online) The α dependence of the branching ratios for $\psi(4040) \to J/\psi\eta$ (upper panel) and $\psi(4160) \to J/\psi\eta$ (lower panel) derived from meson loop. The black solid lines are the results corresponding to $\phi = 0$, and the red dashed lines are evaluated under the assumption $\phi = \pi$. For comparison, the experimental measurements are also presented as cyan and yellow bands for different solutions to the data fitting [10] and blue band for measurements of BESIII Collaboration [12].

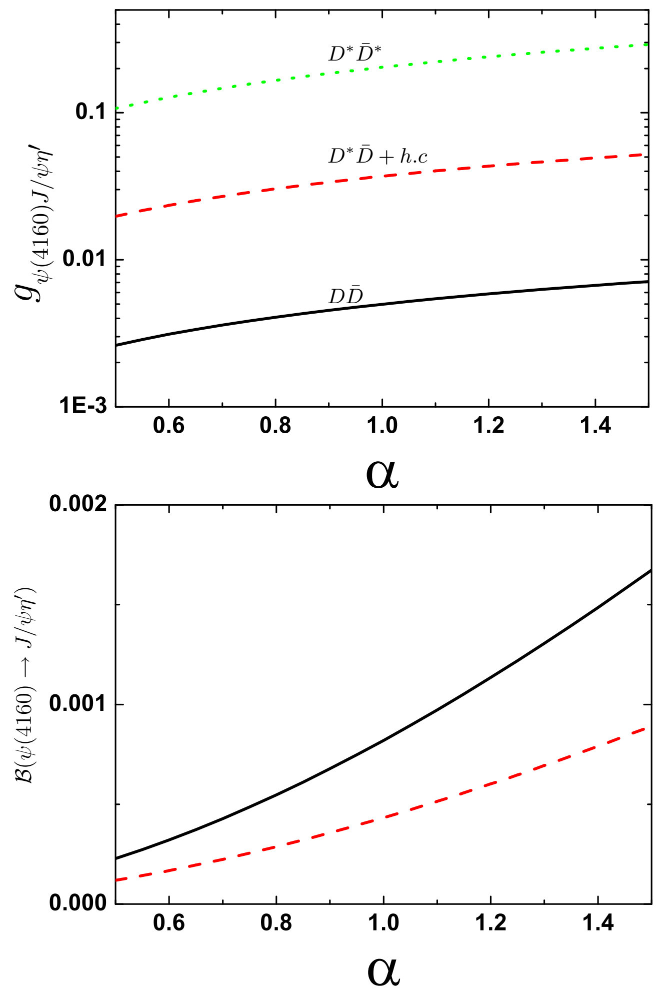

FIG. 4: (color online) The α dependence of the coupling constants (upper panel) and the branching ratio (lower panel) of $\psi(4160) \to J/\psi\eta'$. The coupling constants derived from different intermediate channels are presented and the branching ratios with different $\phi_2 = 0$ and $\phi_2 = \pi$ correspond to the solid and dashed curves in the lower panel, respectively.

$D\bar{D}$ channel can be negligible as indicated by the coupling constants shown in Fig. 2. For simplicity, we just fix the phase angle between $\mathcal{M}_1$ and $\mathcal{M}_2$ to be $\phi_1 = 0$. As for ϕ_2, in the present work we consider two extreme cases, $\phi_2 = 0$ and $\phi_2 = \pi$, which are corresponding to the black solid and red dashed curves in Fig. 3.

For comparison, we also present the experimental measurements of Belle [10] marked as I and II for different solutions and results of BESIII [12] marked as BES with different horizontal bands in Fig. 3. Since the second solutions of the Belle Collaboration is not consistent with the one of the BESIII and CLEO Collaboration, we consider only the first solutions from the Belle Collaboration and results of BESIII Collaboration, which are the cyan and blue bands in Fig. 3. Our theoretical curves with $\phi_2 = \pi$ have a reasonable overlap with the experimental measurements of the Belle Collaboration, which are about $0.7 \sim 1.0$ both for $\psi(4040) \to J/\psi\eta$ and $\psi(4160) \to J/\psi\eta$, while the overlap between theoretical curve and experimental data of the BESIII Collaboration is in the region $\alpha = 0.7 \sim 0.9$. As for the case $\phi_2 = 0$, the overlaps between our results and the experimental measurements appear in a relatively small α region. However, the values of α are still in a reasonable range.

Other than the η transition between $\psi(4040/4160)$ and J/ψ, we also estimate the meson loop contributions to $\psi(4160) \to J/\psi\eta'$. The coupling constants derived from meson loops with different intermediate channels are presented in the upper panel of Fig. 4. Similar to the η transitions between $\psi(4040/4160)$ and J/ψ, $D^*\bar{D}^*$ intermediate channel is dominant and the process via $D\bar{D}$ is negligible. Fixing $\phi_1 = 0$, we can get two theoretical curves with $\phi_2 = 0$ and $\phi_2 = \pi$, which correspond to the black solid and red dashed lines in the lower panel of Fig. 4, respectively. In the region $0.7 < \alpha < 0.9$, the branching ratios are $(4.3 \sim 6.8) \times 10^{-4}$ and $(2.2 \sim 3.6) \times 10^{-4}$

corresponding to $\phi_2 = 0, \pi$, respectively. These results are consistent with the CLEO measurement $< 5 \times 10^{-3}$ with 90% confidence level [11].

IV. SUMMARY

The charmonium above the threshold of a pair of charmed mesons dominantly decays into charmed mesons, which can couple with charmonium and light meson by exchanging a proper charmed meson, such a mechanism, i.e, the meson loop effect, is essential to understand the decay behavior of higher charmonia above the thresholds in obtaining the enhanced decay amplitudes.

Stimulated by the experimental measurements by the Belle and BESIII Collaboration [10, 12], we introduce the meson loop mechanism to study the η transitions between $\psi(4040/4160)$ and J/ψ in an effective Lagrangian approach. The theoretical estimates have shown overlaps with the experimental measurements in a reasonable parameter range. More over, we have predicted the branching ratio of $\psi(4160) \to J/\psi\eta'$ of the order of 10^{-4}, which can be tested by future experiments.

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